

## PHOTOGRAMMETRY AND 3D LASER SCANNING AS SPATIAL DATA CAPTURE TECHNIQUES FOR A NATIONAL CRANIOFACIAL DATABASE

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### *Abstract*

*Photogrammetry is a non-contact, high-accuracy, practical and cost-effective technique for a large number of medical applications. Lately, three-dimensional (3D) laser scanning and digital imaging technology have raised the importance of digital photogrammetry technology to a new height in craniofacial mapping. Under the support of the Eighth Malaysian Development Plan, the Ministry of Science, Technology and the Environment (MOSTE) Malaysia allocated a grant to establish procedures for the development of a national craniofacial spatial database to assist the medical profession to provide better health services to the public. To populate the database with normal and abnormal (malformation, diseased and trauma and burn victims) craniofacial information, it is necessary to evaluate the technology needed to capture the essential data of craniofacial features.*

*The paper provides a discussion on the basic features of the spatial data and the data capture techniques. Both are needed for the establishment of a national spatial craniofacial database. The discussion includes a brief review of the current status of two selected high-accuracy craniofacial spatial data capture techniques, namely, digital photogrammetry and 3D laser scanning. The paper highlights a system which has been developed for a Malaysian craniofacial mapping project.*

*Laboratory tests with mannequins showed that the photogrammetric and 3D laser scanning system could achieve an accuracy exceeding the design specification of  $\pm 0.7$  mm (one standard deviation) for all the measured craniofacial distances. However, tests with two living subjects showed that the accuracy was in the order of  $\pm 1.2$  mm because of facial movement during data capture.*

**KEYWORDS:** 3D laser scanning, close range digital photogrammetry, craniofacial information system, forensic investigation, pre-intervention data for plastic surgery, spatial database

## INTRODUCTION

IN 2001, the Ministry of Science, Technology and the Environment (MOSTE) approved a multi-million dollar grant for research to develop a craniofacial spatial database in Malaysia. Three main research groups are involved in the research. They are the Universiti Teknologi Malaysia (UTM), the Universiti Sains Malaysia (USM) and SIRIM Berhad, which is an appointed government company. In addition, the University of Otago is involved as a data capture consultant. Similar developed databases are limited to a few countries (Farkas, 1994; Kolar and Salter, 1997, p. 11; Ferrario et al., 1999). Essentially, the national database must be able to handle many forms of spatial data in raster format such as charge-coupled device (CCD) camera images, computerised tomography (CT) scanner images and scanned cephalometric radiographs. In addition, many forms of spatial vector data are essential, which may include data obtained from photogrammetric systems, three-dimensional (3D) laser scanning systems or conventional anthropometric measurement techniques. Attribute data are also needed in the database. Examples are patient medical details and pre- and post-surgical intervention data.

For the pre-intervention planning of craniofacial corrective and reconstruction surgery, several forms of 3D spatial data must be available. This craniofacial feature and shape information includes digital 3D craniofacial surface data, 3D soft tissue data, 3D anthropometric measurement, 3D CT scan data, 3D hard tissue data and, occasionally, digital 2D cephalometric radiographs. Also, secondary spatial data such as a patient's parents' or siblings' craniofacial features may be required for planning purposes. These data-sets are essential for planning of a particular type of craniofacial surgery in which accurate pre-surgical data is not available. For example, an accident or burn patient may not have accurate pre-intervention data for reconstructive surgery. Monitoring of post-surgical intervention also requires accurate pre-surgery craniofacial spatial data.

Spatial craniofacial data of the "normal range" group (Farkas, 1994, p. 73) of the population is needed to plan craniofacial reconstruction of malformation patients because the normal data are often used to provide the correct dimensions for surgery (Cutting et al., 1998; Madjarova et al., 1999). Kolar and Salter (1997, p. 232) stated that the absence of adequate comparative data for non-European populations is increasingly becoming a problem for analysing patterns of dysmorphology or for planning surgical corrections. In addition, the normal data is required for forensic applications, namely: (1) identifying a body (skeletal remains), (2) predicting the current profile of the individual and (3) estimating the age of the individual (Giles and Elliot, 1963).

Malaysia is a multiracial country where non-Europeans (Malay, Chinese and Indian) form the bulk of the population. However, the cost of setting up a national database is expensive, in particular for the craniofacial data capture. Therefore, it is essential that proper planning and investigation be carried out before commencing the data capture phase. This research provides an evaluation of current craniofacial spatial data capture techniques and systems. On the basis of the evaluation a combined process was developed employing both photogrammetric and 3D laser scanning technologies.

The paper provides a discussion of the basic features of the spatial data and the data capture techniques. Both are needed for the establishment of a national craniofacial spatial database. The discussion includes a brief review of the current status of two selected high-accuracy craniofacial spatial data capture techniques, namely, digital photogrammetry and 3D laser scanning. The paper also highlights a system which was developed for a Malaysian craniofacial mapping project.

### THE MALAYSIAN CRANIOFACIAL SPATIAL DATABASE

This database was initiated to provide a comprehensive set of craniofacial spatial data of all the racial groups for both corrective and reconstructive surgery. Malaysia has a large number of ethnic groups and tribal subgroups. To populate the database with the craniofacial data of all racial groups would require massive resources. Consequently, the ethnic Malay group was selected for the initial stage of the research. In the subsequent stages, more ethnic groups could be included in the database.

The initial research grant provided the opportunity to develop a photogrammetric/3D laser scanning spatial data capture system. Such a system should be portable, should provide high-accuracy anthropometric linear and angular measurements, should provide high-accuracy 3D surface (skin) models of the craniofacial structure and should provide high-resolution stereo photographs for 3D surface rendering. The grant also provided for the opportunity to set up a comprehensive spatial database, which could be used for corrective and reconstructive surgeries, forensic investigation, safety headgear manufacturing and scientific research. Technically, for a complete representation of the ethnic Malay population, the spatial data should come from males and females of all ages. A total of 3600 individuals were needed for this stage of the project. Details of the spatial data requirement and accuracy aspects are discussed in this section. Next, the reasons for considering the ethnic groups, the inclusion of males and females and of age grouping are addressed.

#### *Spatial Data Requirement*

According to Farkas (1994), a basic craniofacial spatial database should contain a set of anthropometric linear and angular measurements, which could be used to define the shape and size of human craniofacial features. Linear measurements could be projective or tangential (Fig. 1). Examples were the width of the forehead and the circumference of the head, respectively. The angular measurements could be inclination or angles. Examples were the

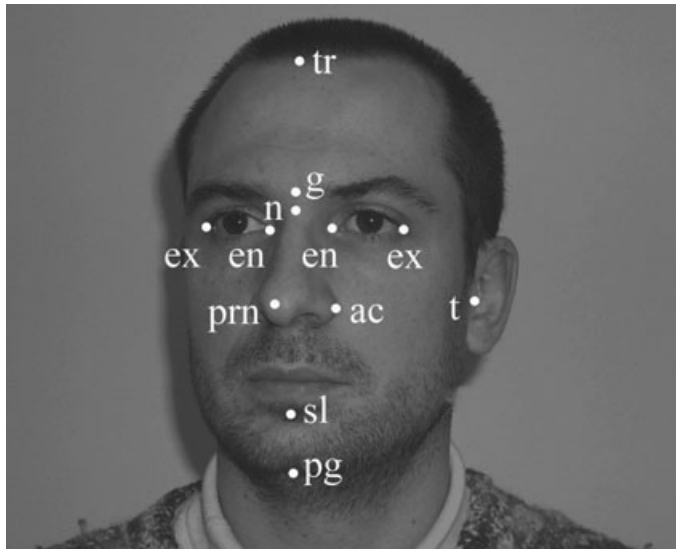


FIG. 1. Standard anthropometric landmarks.

inclination of the anterior surface of the forehead and the mentocervical angle, which was formed by the upper contour of the chin and the surface beneath the mandible, respectively. A complete craniofacial examination required 135 linear and 59 angular measurements (Farkas, 1994). Nevertheless, the basic set of anthropometric measurements was no longer adequate for the modern multi-purpose national database, which would be required for quality corrective and reconstructive surgeries, forensic investigation and scientific research.

After consultation with a group of craniofacial surgeons from USM it was clear that the database should provide data for the following modern applications: (1) evaluating the abnormality of a patient's craniofacial features (for example, asymmetry of the head, face and jaws); (2) pre-surgical intervention planning and post-surgical evaluation of malformed craniofacial features; (3) pre-surgical and post-surgical evaluation of trauma patients; (4) forensic identification of both the living (missing person) and the dead (skeletal remains) and (5) digital 3D models for solid modelling. To satisfy the requirement of the first application, stereoscopic photographs were needed to capture the anthropometric linear and angular measurements. In addition, the stereo photographs should be available for updating and referencing in the future. The data requirements of the second, third and fourth applications were similar. To carry out these applications, 3D models of soft tissue (skin surface) and hard tissue (skull, jaw and teeth) were needed. Photogrammetry, 3D laser scanning technique, structured light modelling and many other developed techniques could obtain the soft tissue model. CT scan and cephalometric radiograph and magnetic resonance (MR) image could provide the hard tissue model. In the fifth application, a 3D solid model of the skin surface and the hard tissue would be needed for patient consultation and classroom illustration purposes. These solid models could be created using rapid prototyping technology (RPT).

### *Spatial Data Accuracy*

This was one of the most important factors in the development of the photogrammetric/3D laser scanning system because it could affect the accuracy of the spatial database. To review the accuracy of the existing databases one needs to go no further than the set of data provided by Kolar and Salter (1997). In the data, a set of manually obtained anthropometric linear and angular measurements was available. The authors provided the population standard deviation of all the important anthropometric measurements of a group of 18-year-old females. The smallest recorded standard deviation of these anthropometric measurements was 0.7 mm. That is, the population showed a deviation of 0.7 mm for the distance connecting two particular anthropometric marks. In other words, a 0.7 mm difference or one standard deviation of the population means in the anthropometric distance between two individuals was not noticeable visually (Farkas, 1994, p. 73; Evereklioglu et al., 2002). However, Kolar and Salter (1997) also argued that a 1 mm inferior dislocation of both endocanthion (en) and exocanthion (ex) (see markers in Fig. 1) could produce an obvious deformity even though the measurements of the eye fissures, length, width and inclination were otherwise symmetrical. Thus, the accuracy in locating some craniofacial landmarks was more important than others.

Gäbel and Kakoschke (1996) reported a clinical requirement of all facial measurements to have an accuracy of 0.1 mm. However, the authors did not refer to any specific standards or specifications. Similarly, Ayoub et al. (1998) stated that a relative accuracy of 0.5 mm is required for work relating to 3D spatial data capture for surgical planning purposes. Again, the specific standards or specifications were not stated. It was difficult to identify the majority of the anthropometric marks for subsequent measurement to such high precision except where a signalled target was placed over the position permanently. Obviously two types of accuracy can be identified: (1) digitising accuracy, which depends on the system and

the signalised target used, and (2) landmark location accuracy, which depends on the anthropologist or the clinician who place the signalised target. On the whole, any substantial improvement in the accuracy also increases the cost of capturing the data. Moreover, the skill of personnel required to capture the data from images can also increase substantially. The demand for skilled personnel in rural hospitals may put a strain on the budget of setting up a national database.

After consultation with a group of craniofacial surgeons it was clear that the existing accuracy of the manually obtained anthropometric measurement was adequate. Consequently, for the first application, a value of 0.7 mm was adopted (Kolar and Salter, 1997) for the overall anthropometric linear measurement accuracy. That is, the stereoscopic photographs should provide an accuracy of  $\pm 0.7$  mm at one standard deviation for all the measured vectors. For the second and third applications an accuracy of  $\pm 2.0$  mm was agreed. This value was determined by the contour tracing method, which is significantly less accurate than the spot elevation method (Wolf and Dewitt, 2000). In conjunction with photogrammetry, a laser-based structured light triangulation technique (3D laser scanning) was used to obtain 3D surface data, recognising the disadvantage of possible patient movement between the stereo photography and the scanning. In view of the 3000 to 4000 patients required for the first phase of the project, the efficiency of such technology as 3D laser scanning outweighed the drawback.

#### METHOD OF CRANIOFACIAL SPATIAL DATA CAPTURE

In view of the accuracy requirement of the spatial data and the amount of data needed to populate the database, it was essential to review the techniques for spatial data capture, particularly, an efficient 3D surface remote measuring technique. D'Apuzzo (2003) and Hu and Stockman (1989) provide discussion on the various remote measuring techniques. The former provides a schematic comparison of three popular techniques based on the accuracy, hardware cost, acquisition time, and processing time and ease of use. The latter gives a list of four basic common remote measuring techniques, which are as follows:

- (1) Stereo disparity: the method simulates the two eyes of a human. Depth can be measured in manual or automated mode. This technique is commonly known as photogrammetry.
- (2) Structured light: an artificial light source such as a laser is used to illuminate a surface with a pattern. A photograph of the patterned surface is used to compute the depth using the triangulation algorithms. A common precise method in this category is known as 3D laser scanning in medical literature.
- (3) Direct ranging or profiling: an example is a laser rangefinder, which measures depth by using the time of travel of the laser beam.
- (4) "Shape-from" techniques: these monocular approaches recover the relative depth from texture, from shading, from contours or from motion; resulting in the surface orientations with respect to a viewer-centred coordinate system.

Many commercial systems have been developed based on these or variants of these techniques. However, it was decided to develop a system based on the technology the research team was familiar with and which would be adequate for the project. Some of the selection factors were based on the information provided in D'Apuzzo (2003). Consequently, only photogrammetry and 3D laser scanning were selected for the project. A brief discussion of the selected techniques and the conventional anthropometric measurement technique are provided below.

### *Conventional Measurement Technique*

No amount of argument in favour of the introduced new method could be considered complete without a proper discussion of the existing technique. Traditionally, craniofacial data was obtained using standard anthropometric instruments such as callipers, measuring tapes, compasses, protractors and angle finders (Kolar and Salter, 1997). Farkas (1994) stated that the anthropometric examiner should be familiar with (a) the areas in which the tip of the instrument used must be pressed to the bony surface to obtain correct measurement and (b) the areas where the instrument barely touches the skin surface at measurement. Farkas (1994) argued that accurate measurement required correct use of the standard anthropometric instruments and knowledge of the peculiarities of the landmarks. Standard tools for curve surface measurement could produce large errors because the line and angle of measurement were subjected to the interpretation of the anthropometric examiner. In addition, both the examiner and the patient were often faced with uncomfortable and lengthy measurement sessions. The conclusion was that only a small number of measurements would still require a standard anthropometric instrument. These measurements would include all the cranial landmarks above the hairline, the circumference of the head and regions not captured by photogrammetry. The missing regions in photogrammetry and 3D laser scanning technique were mainly the result of occlusions and obstruction by hair.

### *Stereo Disparity: Photogrammetry*

Single-, stereo- or multiple-image close range photogrammetry has been used for the recording and mapping of human body parts since the early 1900s (Mitchell and Leemann, 1996). Generally, medical and dental professionals favoured the simple single image measurement techniques. They used the images to determine the length of the feature, the angle between features or relative depth of features (Akimoto et al., 1993; Brusati et al., 1996; Berger et al., 1999; Fanibunda and Thomas, 1999; Nechala et al., 1999). Nevertheless, 3D model generation, contour plots of the craniofacial and 3D anthropometric measurements have been researched extensively (Domokos and Kismartoni, 1974; Newton, 1974; Wright et al., 1974; Deacon et al., 1991; Banda et al., 1992; Ferrario et al., 1995, 1996; D'Apuzzo, 1998, 2002, 2003; Ferrario et al., 1999; Frey et al., 1999).

Images for close range photogrammetry can be acquired using film-based cameras, analogue video cameras or digital still-frame cameras/video cameras. Films must be scanned into digital form using scanners; analogue video must be frame-grabbed into digital form while digital systems output images in digital form directly (Schenk, 1999). By and large, a digital system is the most advantageous because film scanning requires additional resources.

Camera calibration is essential for all photogrammetric cameras which are involved in accurate measurements. Camera calibration software has become more user-friendly for non-metric film-based cameras and digital cameras in recent years (Dowman and Scott, 1980; Fryer, 1989; Beyer, 1992; Peterson et al., 1993; Fraser and Edmundson, 1996; Shortis et al., 1996). The process includes the determination of the CCD format size, principal point of autocollimation, the principal distance, and the radial lens distortion parameters.

Once a stereopair of photographs of the craniofacial area was taken, interior, relative and absolute orientation could be carried out either manually or automatically using soft-copy photogrammetric software (Schenk, 1999). Also, points of interest on the stereomodel could be captured manually or automatically (Schenk, 1999; Wolf and Dewitt, 2000). In the latter, a digital surface model (DSM) of the stereomodel could be obtained instantly. However, there is a small amount of editing required because the craniofacial structure has a complex shape.

Editing could involve the removal of error and the addition of breaklines and ridge lines (Schenk, 1999). Nonetheless, the 3D point cloud created through stereo photogrammetry consists of a set of points with each point having a set of 3D coordinates. The spatial accuracy of the technique depends mainly on the geometry of the images used, the resolution of the CCD camera and the image processing technique. Generally, the desired mapping accuracy can be controlled simply by altering the focal length of the lens, the object distance and the pixel resolution of the CCD of the camera. Relative object space accuracy of 0.5 mm or higher can be achieved using stereo or multiple photographs routinely (Newton, 1974; Burke et al., 1983; Hay et al., 1985; Deacon et al., 1991).

### *Structured Light: Triangulation*

This technique is often known as 3D laser scanning in the medical journals and the same name is used in this paper. The surface of the object is illuminated with an artificial light, which may be any structured light or any shade of pattern. Assuming that the light is projected in a single plane, a triangulation algorithm can determine the depth of the surface (Fig. 2). Details of the mathematics can be obtained in Boyer and Kak (1987), Sanderson et al. (1988) and Hu and Stockman (1989). Generally, the system consists of a structured laser light source, a light projection system and a digital imaging system. The structured laser beam projects an ultra-thin profile on the object, which is photographed by a CCD camera mounted close to the projector. The relative position (a vector) between the internal reference point of the projection system and the camera lens is fixed. In addition, the angle of each projected laser profile plane and the angle of the camera optical axis are calibrated in advance. Subsequently, the  $x$ ,  $y$  and  $z$  coordinates of the object space position of each pixel on the object can be computed using the scale of the photography, the relative positional vector and the known angles. A least squares technique is used to compute a set of optimum 3D coordinates of the object surface. The texture and radiometric value of the CCD images may be added to the 3D data to obtain a realistic surface model of the object. Additional information on the system for medical application can be found in Bush and Antonyshyn

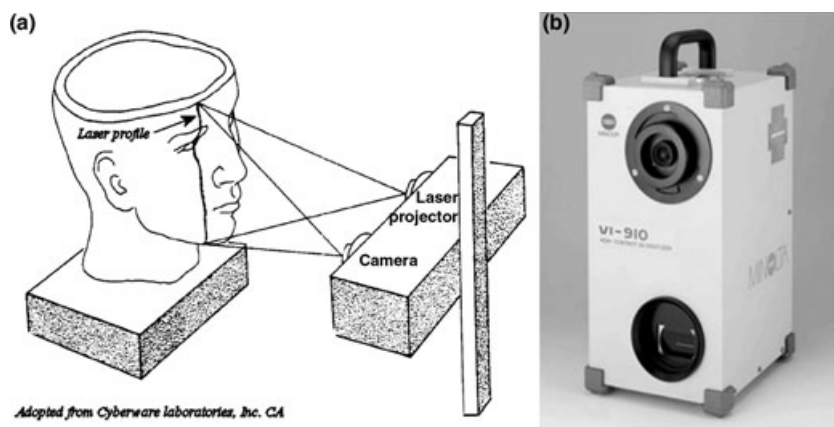


FIG. 2. (a) Structured light triangulation technique. A laser beam is projected onto the surface and the adjacent camera records the position of the beam. During a scan many hundreds of profiles are recorded along the surface. (b) A Minolta VI-910 laser scanner.

(1996), Cacou et al. (1997), Yamada et al. (1998), O'Grady and Antonyshyn (1999) and Bernardini et al. (2001). The spatial accuracy of a triangulation system is dependent on the focal length of the camera, the object distance, pixel size of the CCD camera, the number of cameras used and the mathematics, which determines the centre of the projected light beam. Kuroda et al. (1996) reported a measurement error of 0.05 mm using dual high-precision 3D-VMS250R CCD cameras produced by UNISN, Inc., Osaka, Japan; Bush and Antonyshyn (1996) gave a spatial resolution of 0.5 to 2 mm in *x*, 0.6 mm in *y* and 0.1 to 0.4 mm in *z* (depth) for a single-camera Cyberware 3030RBG digitiser. Minolta gives a depth precision ranging from 0.04 to 0.09 mm for the VI-910 system.

Generally, an off-the-shelf system is fully supported by a suite of software, which includes system calibration, data capture and data editing. To start a scanning session it is necessary to calibrate the system with a supplied calibration chart, which is placed on a rotary stage controller in front of the camera. A view of the scan area is displayed on the system viewfinder. The data capture phase is fully automated. The speed of point capture may range from 15 000 to 230 000 points per second. After a scan the 3D point cloud may be displayed and edited on the computer screen using third-party software such as RapidForm (INUS Technology Inc., Seoul, Korea).

### *Advantages and Disadvantages*

The major advantages of photogrammetry are: it is non-invasive and instantaneous, it offers high accuracy and real-world colour and texture and it provides a permanent record. A permanent record allows re-measurement if it is needed. The major disadvantages are: there is lack of soft (skin and flesh) and hard (bone) tissue registration and there are always occlusions or obstructions on the images. The major advantage of 3D laser scanning is its speed of point capture and its ultra-high accuracy. There are three drawbacks for the present application which are (1) accuracy can degrade substantially if the patient moves during the process of scanning or in between scans, (2) a dark skin colour can affect the intensity of reflected light, (3) creating breaklines for ridges and valleys is both tedious and slow and (4) there is no permanent record as with the photogrammetry technique.

Based on the advantages and disadvantages of the discussion above laboratory tests were carried out. The techniques complement each other. One works at high speed and the other provides a permanent record of high-quality images.

## GENERAL CONSIDERATIONS FOR THE SPATIAL DATA CAPTURE

### *Non-contact Anthropometric Measurement*

The standard anthropometric technique requires physical contact by the anthropometric examiner throughout the measurement session. Physical contact is not always desirable where religious or personal constraints forbid such contact. Conventional anthropometric measurement tools such as a sliding calliper can be very sharp. These tools can cause injury if a child becomes uncooperative during a measurement session. In addition, many areas on the face are very sensitive to touch, which may cause error in the measurement (Newton, 1974). Furthermore, Wright et al. (1974) argued that restraining an uncooperative patient often resulted in grimacing or distortion of the patient's facial features. In view of the fact that photogrammetry and 3D laser scanning are non-contact technologies, approved by the project advisory panel, both techniques are considered vital for the data capture exercise.



### *Manual or Automated Technique for Anthropometric Measurement*

Various authors have discussed advantages and drawbacks of automated anthropometric measurements. Automated anthropometric measurement involves pre-targeting anthropometric mark positions with signalised targets. These targets can be recognised by computer software (Grüen and Baltsavias, 1989; Bush and Antonyshyn, 1996; Ferrario et al., 1996; Cacou et al., 1997; D'Apuzzo, 2002). Ferrario et al. (1996) reported an accuracy of 0.1 mm for all three coordinates of 16 standardised facial landmarks automatically collected using a stereo camera system. Recently, Hattori et al. (2002) reported success with pre-coding targets for automated recognition in industrial vision metrology. Pre-coding targets may be used to identify and digitise the landmark automatically (see Fig. 1 for sample of landmark identification). At this stage there is no plan to implement this technique in the project.

To satisfy the spatial data requirement, which is discussed elsewhere in the paper, each phase of the data capture needs to be examined. Firstly, anthropometric linear and angular data are needed; secondly, a high-quality stereo-image is needed for future updating, referencing and 3D surface rendering; and thirdly, an accurate 3D surface model of the craniofacial area is needed. To obtain anthropometric angular data requires human observation of a photogrammetric stereomodel. The complexity of the arc and angle can only be appreciated by studying the specification given in Farkas (1994) and Kolar and Salter (1997). Consequently, an automated anthropometric landmark measurement technique satisfies the requirement only partially (about 70% of the measurements). However, one major benefit is that pre-signalised targets can be used to provide control points, which can help tie adjacent stereomodels together. In addition, these targets can be used to tie the laser 3D scan coordinates to the photogrammetric coordinate reference system. Consequently, the Ferrario et al. (1996) automation technique is applied for 16 standardised anthropometric landmarks, which are used as control points. The method of applying pre-signalised targets is explained in the next section.

### *Design of Pre-signalised Targets*

For the stereo photogrammetry technique, Ferrario et al. (1999) applied 2 mm reflective markers and Cacou et al. (1997) applied 5 mm diameter blue vellum paper spots on the landmarks. Ferrario et al. (1999) reported an accuracy of 0.1 mm using an automated digitising technique while an accuracy of 0.5 mm using a manual digitising technique was reported by Newton (1974). For the 3D laser scanning technique, Bush and Antonyshyn (1996) used 2 mm diameter fluorescent markers. The authors reported an accuracy of 0.6 mm for signalised landmarks and an accuracy of 1 mm for non-signalised landmarks of a 3D laser scanned model. The present research showed that the use of pre-signalised targets in the stereo photographs gave measurements of equally high accuracy. Also, tests showed that these targets provide high-accuracy connection between adjacent stereomodels. Subsequently, they provided high accuracy for the transformation of the 3D laser scan coordinates to the photogrammetric coordinate reference system. However, it is clear that the placing of the targets required an experienced anthropometric examiner.

### *Photogrammetric Control*

Photogrammetric control for stereo photography of the craniofacial mapping is well documented. In Savara and George (1984) a typical frame was placed over the patient's head;

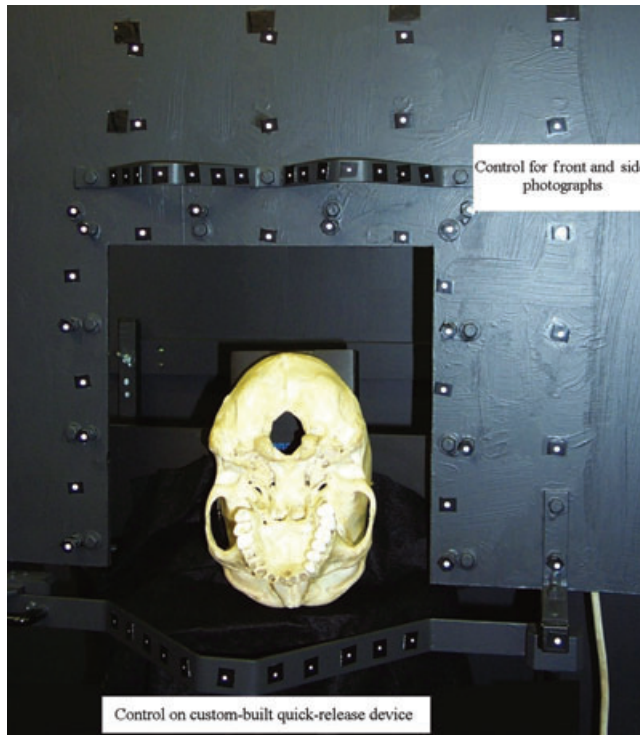


FIG. 3. Control frame for the photogrammetric technique. The positions of the targets provide an optimum control configuration for the side stereo photographs.

This figure appears in colour in the electronic version of the article and in the plate section at the front of the printed journal.

in Peterson et al. (1993) a frame was placed near both sides of the head and in Schewe and Ifert (2000) control targets were placed on a helmet. These three designs almost certainly covered all published photogrammetric control configurations. Frequently, these controls were attached to a cephalostat for study involving the lower craniofacial area. Fig. 3 shows the photogrammetric control configuration, which was based on the designs of Savara and George (1984) and Peterson et al. (1993).

#### *Matching of Photogrammetric Measurement and Laser 3D Scanned Model*

Surface registration was undertaken to determine the transformation parameters between the laser 3D scan and the photogrammetrically derived surfaces (McIntosh and Krupnik, 2002). Theoretically, the two data-sets should refer to the same coordinate system. However, instrumental error and patient movement could introduce a misalignment between the surfaces. McIntosh and Krupnik (2002) argued that a seven-parameter conformal transformation could be manually performed using pre-marked anthropometric landmarks. The process reduces the errors significantly. Consequently, the present research established a set of signalised anthropometric landmarks to provide accurate surface registration. These landmarks, which are depicted in Fig. 1, are *tr*, *n*, *prn*, *pg*, *sl* and *ex*.

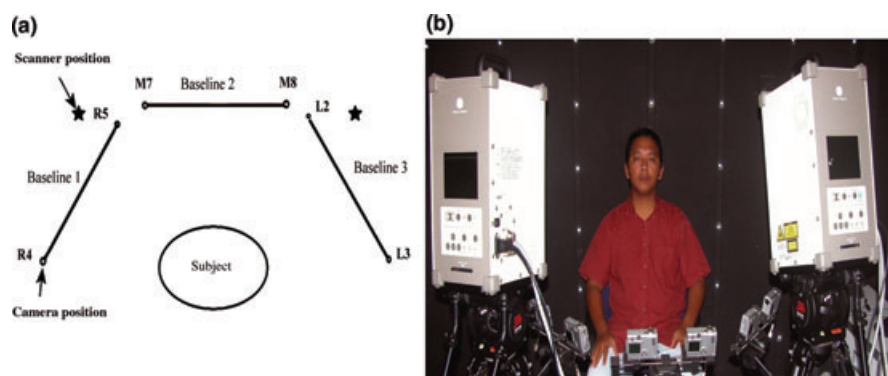


FIG. 4. (a) The craniofacial mapping camera and laser scanner configuration. (b) The Canon PowerShot S400 digital cameras and the laser scanner. Note that the cameras were wired to a single firing device and the prototype console was disconnected for copyright reasons.

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## THE MALAYSIAN CRANIOFACIAL DATA ACQUISITION SYSTEM

### *System Set-up*

A review of existing surgical planning requirements showed that the Malaysian system should be capable of capturing high-quality digital stereo-images covering the whole craniofacial area instantaneously. The instantaneous imaging of the whole area avoided errors which could be introduced as a result of facial movement in between imaging of the remaining craniofacial area. The mapping covers the area from left ear to right ear (including all the anthropometric marks of the ears) and from hairline (*tr*) to the lowest point in the midline on the lower border of the chin (*gn*). To photograph the mapping area simultaneously, three sets of digital stereo cameras were used, which consisted of six Canon PowerShot S400 (4.0 megapixel) digital professional cameras. A synchronised power and shutter switch fired the six cameras simultaneously. In addition, the same craniofacial area was to be scanned by the 3D laser scanning method simultaneously. After the initial evaluation of a few products, the Minolta VI-910 3D digitiser was selected and two of these scanners were used to scan the whole craniofacial area (Fig. 4). A minimum of four well-distributed photogrammetric control points was allocated to each stereopair of images. Signalised targets were used for all standardised anthropometric landmarks. The targets were also used for the registration of the photogrammetrically derived coordinates with the coordinates obtained using the 3D laser scanning technique.

### *Calibrating the Cameras*

To provide regular camera lens calibration for the six digital stereo cameras or when a new camera is added, a simple portable device was built for the purpose (Fig. 5). The calibration range required to be photographed with a high-precision Invar bar in the middle of it. The range can be rotated to allow four or more convergent photographs to be taken for a self-calibration. In the bundle adjustment, the lens parameters can be determined accurately (Beyer, 1992; Atkinson, 1996; Fraser, 2000). The process is simple because it is not essential to calibrate the range beforehand.

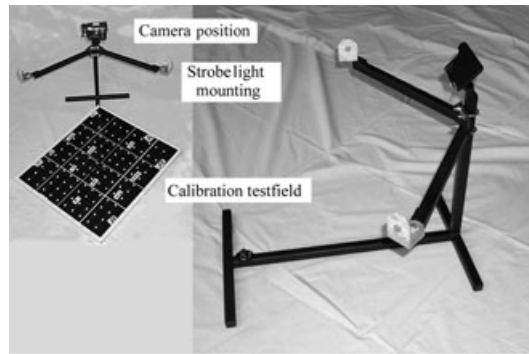


FIG. 5. A purpose-built camera calibration system.

### *Evaluating the Camera Synchronisation Device*

To determine the suitability of low-cost digital cameras for high-accuracy anthropometric landmark measurement, it was necessary to study the reliability of the synchronisation technique. The cameras were connected to an electronic shutter activator which was developed by Graphic Media Research, Cannon Falls, Minnesota, USA. A shallow press of a button prepared the cameras for the synchronisation. Subsequently, a deep press activated the shutters simultaneously. To determine whether the three stereopairs of photographs were taken simultaneously, a simple test was carried out. A plumb bob was hung from the ceiling above the photogrammetric control frame (Fig. 6). A white marker was placed on the plumb string just above the plumb bob. The plumb bob would be released at a specified elevation and allowed to go through a few full swings. Subsequently, the cameras' shutters were released when the plumb bob moved close to the lowest point of the swing while viewing from camera M8 (Fig. 4). The entire test procedure was repeated nine times. The cameras were turned off between each set of tests. Both Australis and DVP software were used to compute the position of the white marker for each set of stereopairs. In total 45 stereopairs of images were relatively oriented and the position of the white markers was subsequently computed from each stereopair.

### *Calibrating the Photogrammetric Control Frame*

The photogrammetric control frame (Fig. 3) requires similar calibration. To calibrate the control frame four or more convergent photographs are taken with a high-precision Invar scale bar placed in the middle of the control frame. Again, a bundle adjustment is needed to determine the coordinates of the signalised targets. It is not necessary to have any previous known control point in the adjustment as in the case of an absolute orientation of a stereomodel.

### *Assessment of the Quality and Reliability*

To monitor the quality and reliability of the measurement obtained by the photogrammetric/3D laser scanning system, the system needed to be tested using a rigidly constructed mannequin. Initially, signalised targets are placed on the anthropometric landmarks of the mannequin. The coordinates of the signalised targets are determined by a set of convergent

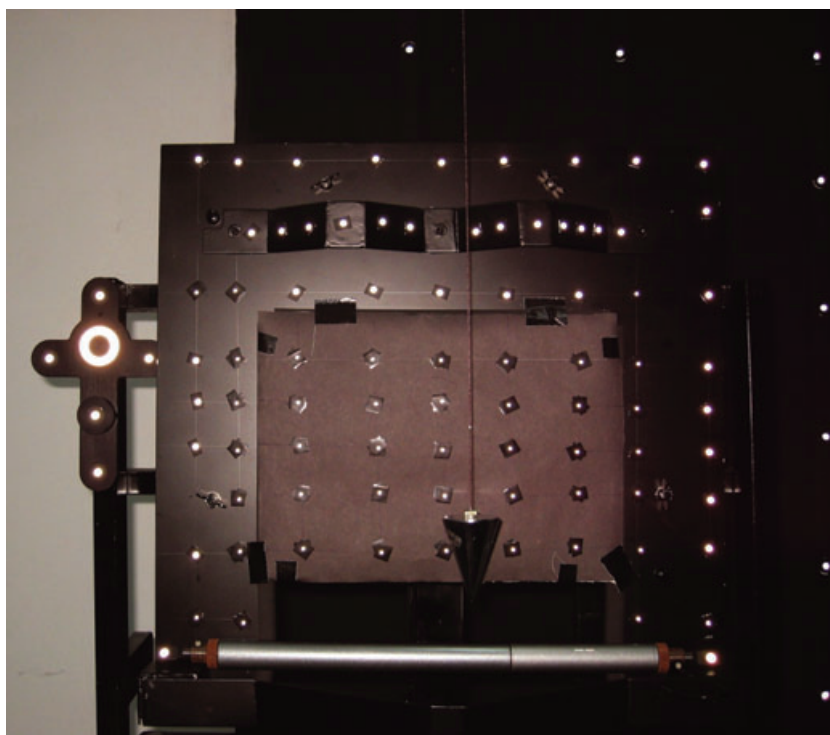


FIG. 6. Camera synchronisation test. A plumb bob was allowed to swing in front of the photogrammetric control frame. Note that a stiff board was placed in the “hole for the patient’s head” to provide more targets for photogrammetric relative orientation.

This figure appears in colour in the electronic version of the article and in the plate section at the front of the printed journal.

images and a bundle adjustment on the image coordinates of targets on the photographs (Atkinson, 1996; Fraser, 2000).

Subsequently, the system captures the data of the craniofacial area of the mannequin. The coordinates of the signalised targets on the mannequin are determined from the oriented stereo-image 3D models. The computed coordinates are checked against the coordinates that are obtained by the initial bundle adjustment for any discrepancies or any changes in the error size. Also, the triangulated 3D coordinates of the signalised targets of the mannequin are checked against the control set of coordinates for any discrepancies in the triangulated 3D coordinates.

### *Operating the Prototype System*

Two computers control the prototype system: one operates the three sets of Canon digital stereo cameras while the other operates the two Minolta VI-910 scanning systems. The patient’s head is positioned on the headrest. The control frame is positioned around the patient’s craniofacial area (Fig. 3). The system console is manoeuvred into position by means of a locking device, which ensures that the object distance of the cameras remains consistent between set-ups. All three sets of stereo cameras are positioned over pre-identified craniofacial areas preceding the photography. Once the images are recorded, the VI-910 systems are

activated in succession. As the head of the patient is positioned tightly in a headrest and the patient is directed to stare at a specific point on the console, the position of the head is maintained during the short operation. The prototype and the software are being improved and revised regularly. Consequently, it is difficult to give an accurate time for each set-up. However, the average time required for an adult patient is roughly 20 min. The system will not be used on children until further improvements are made.

## RESULTS

### Camera Calibration

The results of the camera calibration of the six cameras using Australis camera calibration software are provided in Table I. In the table, it can be seen that the principal point offsets ( $x_p$  and  $y_p$ ) vary considerably between cameras. As the camera-to-object distance and lens setting were set approximately the same (see Figs. 4 and 5) no error was expected from this source.

### Results of the Stereo Photogrammetry Test

A DVP digital photogrammetric workstation (DVP-GS, Beauport (Qc) Canada) was used to obtain the coordinates of the pre-signalised targets. The results showed that the photogrammetry technique achieved an accuracy of  $\pm 0.5$  mm at one standard deviation for any measured distance between two anthropometric landmarks.

### Results of Camera Synchronisation Test

Table II shows the mean distance of the plumb bob displacement as a result of non-synchronisation of the cameras' shutters. The stereopair from cameras L2 and L3 provided a reference position. Subsequently, four stereopairs in relation to camera L2 were oriented and the position of the white marker was computed. These stereopairs were denoted as L2–R4, L2–R5, L2–M7 and L2–M8. The  $x$  coordinate of the white marker was used to show whether the stereopairs were taken before or after the reference stereopair. The  $x$  coordinate could be used for this purpose because the plumb bob moved from left to right across the control board. Subsequently, the displacement would represent either negative or positive time delay.

TABLE I. The lens parameters of six Canon PowerShot S400 digital professional cameras.

Camera ID	$c$	$x_p$	$y_p$	$k_1$	$k_2$	$k_3$
L2	7.356	-0.037	0.083	2.4E-03	-3.3E-05	-1.3E-07
L3	7.247	-0.003	-0.052	2.5E-03	-2.9E-05	-1.0E-07
M4	7.295	-0.074	-0.065	2.4E-03	-1.2E-05	-9.9E-07
M5	7.232	0.042	0.064	1.8E-03	1.1E-05	1.8E-06
R7	7.262	0.034	-0.022	2.1E-03	-2.3E-06	-1.6E-06
R8	7.151	-0.065	-0.037	1.6E-03	1.1E-04	-7.1E-06

TABLE II. Results of camera synchronisation test.

Stereopair ID	L2–L3	L2–R4	L2–R5	L2–M7	L2–M8
Mean distance (mm)	Reference	4.9	0.5	4.5	-4.0
Standard deviation (mm)		1.5	1.2	1.5	2.7
Approximate time delay (ms)		8	0.8	7.5	6.6

A negative delay means the camera shutter opens before L3 and a positive delay means the camera shutter opens after L3. The negative or positive delays were verified by the value of the  $x$  coordinate displacement. Equivalence in time for the delay is also provided in the table. Somia et al. (2000) stated that normal eyelids blink at a velocity of about  $205 \text{ mm s}^{-1}$  and it takes about 0.22 s for the eyelid to complete a cycle. At a velocity of  $205 \text{ mm s}^{-1}$  a time delay of 8 ms equates to 1.6 mm. No other facial movement has been reported to move at a higher speed. Consequently, the time delay was considered acceptable for the project.

*3D Laser Scanning: Minolta VI-910*

Fig. 7 shows the output of the scanners. The figure also shows some of the drawbacks of the scanned data, that is, poor texture and occlusions. Test results of the Minolta VI-910

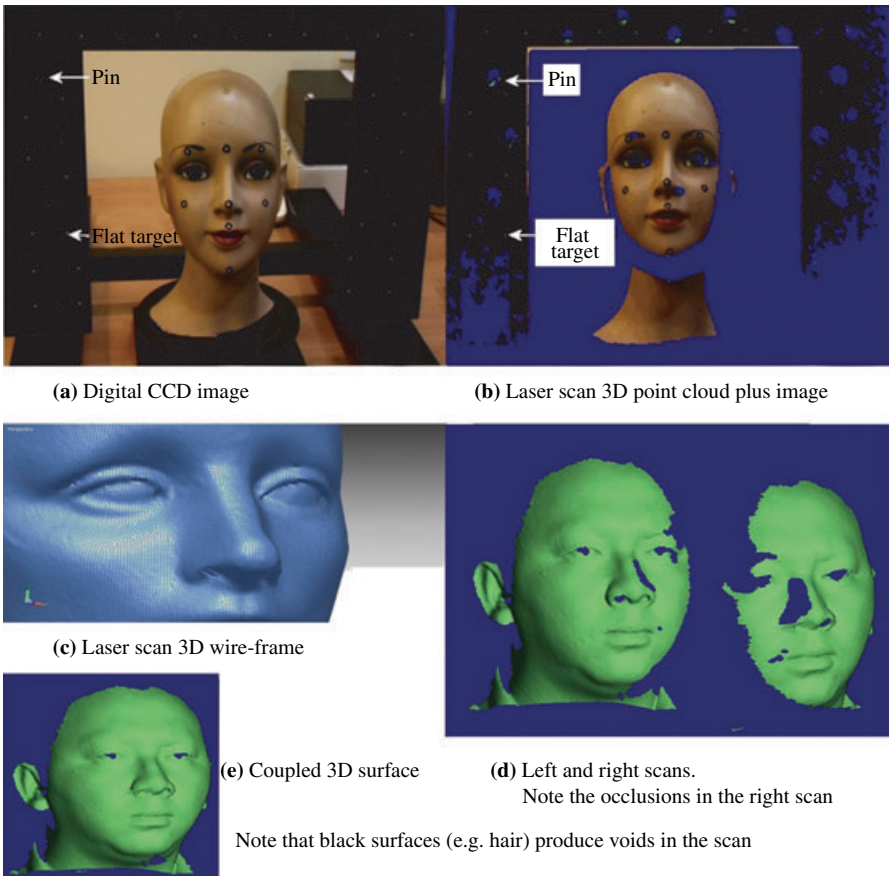


FIG. 7. (a) Left image was captured by a CCD camera. (b) Right image was a representation of the point cloud captured by the Minolta VI-910 laser scanner. (c) Laser scan 3D wire-frame. (d) Scan from the left and right scanner. (e) Scan from left and right scanners were coupled together. Note the contrast between the retro-targets on the “flat” surface and the retro-target on 8 mm diameter pins (varies from 10 to 50 mm in length) in (a) and (b). This figure appears in colour in the electronic version of the article and in the plate section at the front of the printed journal.

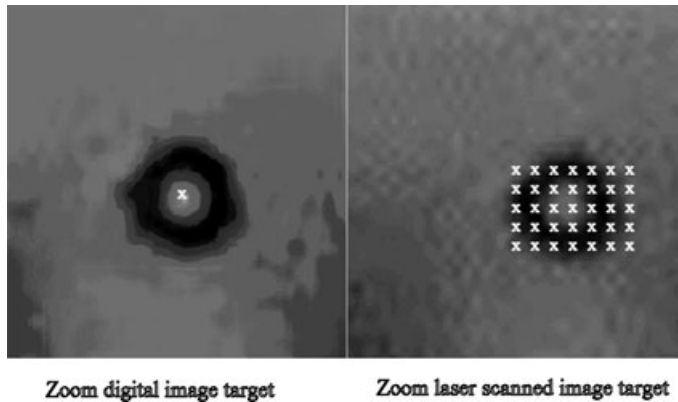


FIG. 8. Left image shows the position digitised by the photogrammetric technique. Right image shows the possible positions which can be digitised on the laser scan.

showed that the system achieved an accuracy of  $\pm 0.1$  mm, which was close to the current published values. A small sample of the manual registration between the photogrammetric 3D model and scanned point cloud showed an average rms discrepancy of  $\pm 0.6$  mm. However, the procedure of the registration of the two 3D surfaces required further refinement (Fig. 8). In the figure, one could see the difficulty of selecting the correct point amongst the point cloud in the scanned 3D model. In addition, the accuracy for living craniofacial features was significantly reduced as a result of patient movement, especially for the younger population. Laboratory tests with two living subjects showed that the accuracy was of the order of  $\pm 1.2$  mm because of facial movement during data capture.

## DISCUSSION

A number of problems have been encountered in the project so far. Some have been solved while others are being worked on. Initially, the problems involved synchronising eight digital cameras. The problem was solved when more advanced off-the-shelf medium-resolution digital cameras appeared on the market and Graphic Media Research, Cannon Falls proved able to produce a synchronisation device for up to eight cameras for the project. The next problem involved the positioning of the patient's head in the headrest. Having a reference mark on the system console, which the patients could focus their eyes on during the photography and 3D laser scanning, solved the problem. Other problems involved stereo digitising and laser 3D scan editing. Proper training and customising software were the main reasons. Tackling these problems requires much longer time and a lot more effort. At present, a team of seven M.Sc. and four Ph.D. students, technicians and programmers are involved in resolving these problems.

The prototype system is suitable for the capture of the planned 3600 young and adult patients. For the system to be infant-friendly, it will require a few structural changes, namely: (1) the size of the chair, (2) the location of the cameras and the laser 3D scanners, and (4) the lighting. Consequently, the option is to build a smaller console for infants.

The system was designed for use by medical lab technicians. The research phase should be completed by 2005. Medical lab technicians would be given the tasks of taking the stereo photographs and running the laser 3D scanners. Medical Imaging Research Group (MIRG) technicians at the Universiti Teknologi Malaysia campus would process the stereo photographs



and the laser 3D scans. In addition the MIRG would employ data entry personnel to populate the craniofacial database.

# CONCLUDING REMARKS

In the paper, the use of digital photogrammetry and 3D laser scanning technology has been discussed for the spatial data capture of craniofacial features. Matters concerning the type of spatial data needed for a national database and the particulars relating to the design of an accurate stereo-imaging and 3D laser scanning system have also been discussed. In addition, a short discussion was provided on the procedure concerning the quality control of the data captured by the photogrammetric/3D laser scanning system. Also, test measurements showed that the accuracy met the specifications for craniofacial data capture for the database.

While the cost of the system is high because of the introduction of the 3D laser scanning technology, it is believed the initial cost is easily offset by the high labour cost for 3D surface model generation using the conventional stereo-image matching photogrammetric technique and the time involved in the process. The system requires a minimum time to populate the national database with quality data.

Research is in progress to customise software and to optimise the stereo digitising and 3D laser scan editing techniques. In addition, tests are being carried out on the use of natural points for joining stereomodels and an advanced electronic device for camera/scanner synchronisation. The results of the research will be published in the near future.

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### Résumé

*La photogrammétrie se présente comme une technique rentable, pratique, de haute précision, sans contact avec l'objet, valable pour un grand nombre d'applications médicales. Dernièrement les techniques à base d'images numériques ou de balayage 3D par laser ont accru l'intérêt et l'importance de la photogrammétrie numérique pour la cartographie de la boîte crânienne. Le Ministre de la Science, de la Technologie et de l'Environnement de Malaisie (MOSTE), dans le cadre du 8ème plan malaisien de Développement, a accordé une subvention pour définir les procédures d'établissement d'une base de données 3D nationale sur la boîte crânienne, et permettre au corps médical de fournir de meilleurs soins de santé*

à la population. Pour alimenter cette base de données en données crâniennes normales et anormales (venant de victimes de brûlures, traumatismes, maladies ou malformations), il faut évaluer d'abord les technologies nécessaires à la saisie des principales données caractérisant la boîte crânienne.

On examine dans cet article les éléments de base relatifs à ces données 3D et aux techniques de saisie, l'ensemble des deux étant nécessaire pour établir cette base de données 3D nationale sur la boîte crânienne. On analyse rapidement l'état actuel des deux techniques évoquées ci-dessus, à savoir la photogrammétrie numérique et le balayage 3D par laser. On s'attache dans cet article au système mis en œuvre dans le cadre du projet malaisien de cartographie crânienne.

Les essais en laboratoire avec des mannequins ont montré que le système de photogrammétrie et de balayage laser utilisé pouvait fournir une précision supérieure aux spécifications affichées de  $\pm 0.7$  mm (écart-type), sur toutes les distances mesurées sur la boîte crânienne. Toutefois les essais sur des êtres vivants ont montré que la précision tombait à environ  $\pm 1.2$  mm, à cause des mouvements qui se présentaient en cours de saisie.

### Zusammenfassung

Die Photogrammetrie ist ein berührungsloses, hochgenaues, zweckmäßiges und kostengünstiges Verfahren für eine große Anzahl medizinischer Anwendungen. Durch das 3D Laserscanning und digitale Aufnahmetechnologien hat die Bedeutung der Digitalen Photogrammetrie für die Modellierung von Schädel- und Gesichtsoberflächen stark zugenommen. Mit Unterstützung des Achten Malaysischen Entwicklungsplans wurde vom Ministerium für Wissenschaft, Technologie und Umwelt (MOSTE) in Malaysia ein Projekt zur Entwicklung von Verfahren für die Aufstellung einer nationalen Gesichts- und Schädel Datenbank eingerichtet. Diese Datenbank soll die Medizin bei der Bereitstellung verbesserter Gesundheitsdienste unterstützen. Die Datenbank soll mit Informationen über normale und abnormale Schädel- und Gesichtsoberflächen gefüllt werden. Letztere können durch Missbildungen, durch Erkrankungen, Verletzungen oder Verbrennungen hervorgerufen werden. Es ist absolut erforderlich die Technologie zu evaluieren, die es erlaubt die wesentlichen Daten von Gesichts- und Schädeloberflächen zu erfassen. Dazu dient dieser Beitrag, der sowohl die räumlichen Daten zur Modellierung als auch die Datenerfassungstechniken vorstellt. Die Diskussion beinhaltet eine kurze Analyse des aktuellen Standes zweier hochgenauer Techniken, nämlich der digitalen Photogrammetrie und dem 3D Laserscanning. In dem Beitrag wird ein System besonders hervorgehoben, dass in dem malaysischen Projekt entwickelt wurde. Laboruntersuchungen mit Schaufensterpuppen haben gezeigt, dass dieses System, gestützt auf Photogrammetrie und Laserscanning, eine Genauigkeit von  $\pm 0.7$  mm (Standardabweichung) für alle gemessenen Distanzen im Bereich des Schädels, bzw. Gesichts erreicht, was die Erwartungen übertraf. Jedoch haben Versuche mit lebenden Personen gezeigt, dass die Genauigkeit nur noch im Bereich  $\pm 1.2$  mm lag, was auf Gesichtsbewegungen während der Aufnahme zurückzuführen war.

### Resumen

La fotogrametría es una técnica sin contacto, de alta precisión, económica y práctica para un gran número de aplicaciones médicas. En los últimos tiempos, las

*tecnologías de imágenes digitales y de escaneado láser en 3D han acrecentado la importancia de la fotogrametría digital en el campo de la cartografía craneofacial. Con el apoyo del Octavo Plan Malayo de Desarrollo del Ministerio de Ciencia, Tecnología y Medio Ambiente (MOSTE), Malasia ha proporcionado financiación para establecer unos procedimientos para el desarrollo de una base de datos espacial craneofacial nacional, ayudando así a la profesión médica a proporcionar mejores servicios de salud a la población. Con el objeto de almacenar en la base de datos información craneofacial tanto de casos normales como anormales (víctimas de malformaciones, epidemias, traumas y quemados), se hace necesario evaluar la tecnología necesaria para capturar los datos esenciales de los rasgos craneofaciales.*

*El artículo examina las características básicas de los datos espaciales y las técnicas de captura de datos. Ambos son necesarios para establecer una base de datos craneofacial espacial nacional. El examen incluye una breve revisión del estado actual de la fotogrametría digital y el escaneado láser 3D, las dos técnicas seleccionadas para la captura de datos espaciales de alta precisión. El artículo describe un sistema que ha sido desarrollado por un proyecto malayo de cartografía craneofacial.*

*Las pruebas de laboratorio con maniquíes demostraron que nuestro sistema fotogramétrico y de escaneado láser 3D puede alcanzar una exactitud que supera la especificación de diseño de  $\pm 0.7$  mm (una desviación típica) para todas las distancias craneofaciales medidas. Sin embargo, los ensayos realizados con dos personas mostraron que la exactitud estaba en el orden de  $\pm 1.2$  mm, un valor más alto que es resultado del movimiento facial durante la captura de los datos.*